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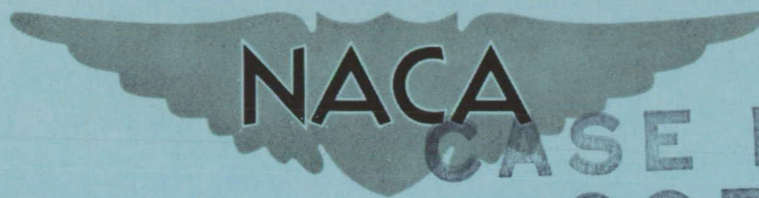
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RESEARCH MEMORANDUM

PHOTOGRAPHIC STUDIES OF PREIGNITION ENVIRONMENT AND
FLAME INITIATION IN TURBOJET-ENGINE COMBUSTORS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

PHOTOGRAPHIC STUDIES OF PREIGNITION ENVIRONMENT AND FLAME

INITIATION IN TURBOJET-ENGINE COMBUSTORS

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SUMMARY

An investigation was conducted to gain knowledge of the preignition environment and the manner of flame initiation in turbojet-engine combustors by the use of transparent combustors and photographic methods. The effect of combustor operating variables (air flow and pressure, fuel flow and temperature) and fuel-nozzle design on fuel-spray and air-flow patterns in the combustor primary zone at critical starting conditions were studied. Flame propagation in a full-scale turbojet engine was also studied. Qualitative photographic results are presented.

The concept of reverse air flow in the center of the combustor primary zone was substantiated; however, the air-flow patterns varied considerably with time. The air turbulence in the combustor markedly improved fuel atomization. Air velocity showed a greater effect than air pressure or fuel temperature on atomization; however, change in fuel-nozzle design resulted in the greatest improvement. The combustor-liner walls and the spark electrodes were wetted thoroughly by the fuel. The manner of the initial flame spreading was predictable from the cold-flow air patterns. These results aided in understanding the effect of combustor operating conditions, fuel-spray characteristics, and design variables on combustor ignition characteristics.

INTRODUCTION

The problem of initiating combustion in the turbojet engine is aggravated by increased operational altitudes and by the use of fuels of low volatility (MIL-F-5624A grade JP-4). Investigations conducted at the NACA Lewis laboratory have shown the effect of several variables on the ignition characteristics of turbojet-engine combustors both in full-scale engines and in single tubular combustors. Some of these variables are fuel volatility (references 1 to 4), ambient air and fuel temperature (reference 2), spark-gap location (references 4 and 5), fuel-spray characteristics (references 6 and 7), and spark energy and repetition rate (references 3, 4, 8, and 9); all are of importance in establishing the ignition limits.

Knowledge of the preignition fuel and air environment at the ignition source in the combustor would aid in an understanding of why the previously mentioned ignition variables have pronounced effects on the ignition limits. For example, knowledge of this environment may explain why the spark energies required for ignition in a turbojet-engine combustor, where fuel is injected as a liquid spray, are many times (a factor of 100 or more) greater (references 3 and 8) than the minimum spark energies required to ignite flowing, premixed gaseous-fuel and air mixtures (reference 10).

A general insight into the details of fuel and air flow in a turbojet combustor would add to the present knowledge of fuel-spray formation and air-flow patterns and aid in understanding the ignition problem so that means can be developed to provide ignition over the required range of starting conditions with the low-volatility fuels and with a minimum of ignition energy.

Several studies of fuel-spray formation as seen in still air have been reported (references 2, 6, and 7); however, the behavior of these sprays in a flowing air environment as it exists in a turbojet combustor at starting conditions has received little attention. Some preliminary results showing reverse air flow in a combustor are reported in reference 11.

As a part of the general turbojet ignition research program at the NACA Lewis laboratory, studies of the preignition environment and of flame initiation in the combustor have been undertaken. This report presents preliminary qualitative data obtained in an investigation of the effects of combustor operating variables on fuel-spray and air-flow patterns in the vicinity of the spark plug at critical starting conditions. In addition, motion pictures of flame initiation in a combustor and flame propagation in a full-scale turbojet engine are included.

A transparent plastic tubular combustor was used for cold-flow visual and photographic studies of the fuel-spray and air-flow patterns; a quartz and glass section in another tubular combustor was used for the flame initiation studies.

The development of the photographic techniques for obtaining the data required considerable time and form an important phase of this investigation. These techniques are described in detail in the appendix. (

The motion pictures obtained in this investigation have been prepared as a sound-film supplement to this report and may be obtained on loan from the NACA Headquarters, Washington, D. C.

APPARATUS AND PROCEDURE

Cold-Flow Combustor Studies

Combustor installation. - The effects of combustor operating variables on fuel-spray and air-flow patterns were studied in a full-scale transparent plastic model of a single tubular J33 combustor (fig. 1). The outer shell was 1/4 inch in thickness and the liner, 1/16 inch in thickness. The fuel nozzles studied were: (1) a fixed-area swirl-type nozzle currently used in this model combustor (rated at 40 gal/hr at 100 lb/sq in. pressure), and (2) an experimental variable-area nozzle (reference 6). The variable-area nozzle was modified to reduce the included spray cone angle with JP-3 type fuels to about 100° in the starting flow range of 15 to 50 pounds per hour. The variation of fuel pressure drop across the nozzle with fuel flow for both of these nozzles is shown in figure 2.

The general arrangement of the combustor installation is shown in figure 3. Air from the laboratory supply system was passed through the combustor to the laboratory exhaust system with both the flow rate and pressure manually regulated by remotely operated valves. A portion of the air was bypassed through an electric heater and remixed with the supply air to control air temperature. In order to simulate more critical starting conditions, the inlet-air temperature was maintained as low as possible (50°F) without frosting the transparent combustor walls.

Fuel (MIL-F-5624A grade JP-3), sprayed into the transparent combustor, passed through a water-spray flame arrester and was subsequently burned in another combustor located downstream of the transparent combustor. The temperature of the fuel was regulated by bypassing a portion of the fuel through a coil immersed in a cooling bath.

Instrumentation. - Air flow to the installation was metered by a square-edged orifice, installed according to A.S.M.E. specifications, upstream of all regulating valves; the fuel flow to the combustor was measured by a calibrated rotameter. The inlet-air temperature was measured by a single-junction iron-constantan thermocouple at plane 1-1 (fig. 3) and the inlet-air pressure, by two, six-point total-pressure rakes and a static-pressure tap located at plane 2-2 (fig. 3). For control purposes, the exhaust-gas temperature was measured at plane 3-3 (fig. 3) by two rakes of three-junction radiation-shielded chromel-alumel thermocouples. The temperature and the pressure of the fuel were measured by a single-junction iron-constantan thermocouple and by a Bourdon-type gage, respectively; both measurement points were located in the fuel line immediately before the transparent combustor. All temperatures were indicated on self-balancing potentiometers.

Combustor photographs. - The camera positions and lighting arrangements used for obtaining the reported photographic data are shown in figure 4. After establishing the combustor operating conditions, the photographs were obtained as described in the appendix.

Burning-Flow Combustor Studies

Combustor installation. - The study of flame spreading from the ignition spark was made in a single tubular J33 combustor in which the upstream end was replaced by a transparent section. For the initial tests, a 4-inch section of the liner and outer shell were reproduced in transparent plastic similar to the combustor pictured in figure 1. A single plastic liner withstood about 40 short-duration (a few seconds) ignition test runs. In order to obtain a larger field of view of the combustor primary zone, a 10-inch length of the liner was fabricated from quartz with a 1/10-inch wall thickness; a corresponding section of the outer shell was fabricated of 3/8-inch thick pyrex. An exploded view of this combustor is shown in figure 5. The wall cooling slots in the plastic liner (fig. 1) were replaced by round holes of equivalent area in the quartz liner for ease of fabrication.

The combustor was connected to the laboratory service systems by the ducting shown diagrammatically in figure 6. The installation was similar to that used for the cold-flow combustor studies, except that a fuel-fired preheater was used.

Fuel (MIL-F-5624A grade JP-3) was supplied to the test burner from a nitrogen-pressurized 2-gallon mixing tank equipped with a recirculation pump. The initial surge of fuel to simulate starting was provided by a quick-opening valve in the fuel line. The fixed-area and the variable-area fuel nozzles used in the cold-flow combustor were also used in this study.

Instrumentation. - The air flow to the transparent combustor was metered by a calibrated variable-area orifice, installed according to A.S.M.E. specifications. The fuel flow to the transparent combustor was indicated by the nozzle differential pressure, measured by a pressure gage.

The temperature of the inlet air was measured by a single-junction iron-constantan thermocouple, located at instrumentation plane 1-1 (fig. 6). The inlet-air pressure was measured by a static-pressure tap at plane 2-2 (fig. 6). The transparent-combustor-outlet gas temperature was measured at plane 3-3 (fig. 6) by two, two-junction, chromel-alumel thermocouples. The exhaust-gas temperature from the service burner was measured at plane 4-4 (fig. 6) by a single-junction chromel-alumel thermocouple. All temperatures were indicated on self-balancing potentiometers.

Flame initiation motion pictures. - Flame initiations in the burning-flow combustor were photographed from several camera positions as shown in figure 7. The photographic techniques and operating methods required are described in the appendix.

Full-Scale Engine Studies

During full-scale turbojet-engine starting tests, normal-speed motion pictures of ignition trials were obtained which indicate combustor-to-combustor flame-propagation characteristics. Pictures were taken of the turbine outlet (with the tail pipe removed) during engine starts with fixed-area and with variable-area fuel nozzles. These motion pictures are presented as a part of the film supplement to this report. The engine and its instrumentation are described in reference 7; the results of the starting tests are presented in detail in references 6 and 7.

RESULTS

Fuel-Spray Characteristics

Combustor-ignition difficulties have frequently been attributed to fuel-spray characteristics at the low flow rates encountered during engine starting. Most observations of spray characteristics have been made with the fuel nozzle spraying into quiescent air (references 2, 6, and 7). Examples of fuel sprays from the fixed-area fuel nozzle, as seen in quiescent air, are shown in figure 8. Photographs of the spray in the cold-flow transparent combustor under flowing-air conditions are shown in figure 9. A comparison of figures 8(a) and 9(b) (both at nearly the same fuel flow) indicates that the air-flow currents in the combustor can have a marked effect on the spray formation.

For a more complete study of the effect of combustor air currents on spray formation, it was desirable to choose critical combustor ignition conditions and to take motion pictures of the fuel sprays. Test conditions were therefore selected from figures 10(a) and 10(b), which present ignition-limit curves obtained in an earlier investigation with a J33 combustor (reference 2). In figure 10(a) the curve represents the minimum fuel flow necessary for ignition as a function of fuel temperature; in figure 10(b) the curve represents the minimum combustor-inlet pressure at which ignition can be obtained as a function of air velocity (air velocity as used herein is based on the maximum cross-sectional area of the combustor, the inlet-air density, and the mass air-flow rate, unless otherwise noted). The curve of figure 10(b), a cross plot at constant critical starting fuel flow, was obtained from a plot of altitude against fuel flow at various engine speeds in reference 2. The operating conditions chosen for the present investigation are indicated in figures 10(a) and 10(b) by the test points. The significant operating

variables studied include fuel flow and fuel temperature (fig. 10(a)) and combustor-inlet-air pressure and combustor-inlet-air velocity (fig. 10(b)). Although the ignition-limit data of figure 10 include a continuous variation in combustor-inlet-air temperature along the curve, the present investigation was restricted to constant temperature (50° F) operation. The fuel-spray formations in the combustor can best be observed in the motion-picture film supplement; however, the selected strip sequences presented in figures 11 to 14 indicate the effects of combustor variables on spray formation. The wetting of the walls of the combustor by fuel caused the blurred appearance of some of the photographs.

Effect of air currents. - A comparison of figure 8 with figures 11 to 14 shows that fuel atomization was improved by the air-flow currents in the combustor. The motion pictures indicate that a reverse flow of air in the center of the combustor caused the spray to flutter and thus improved atomization. Various phases in this fluttering of the spray may be seen in figures 11 to 14.

The liner walls and the spark plug were wetted with fuel at all fuel flows investigated. The amount of liquid fuel on the liner walls and on the spark electrodes increased with the degree of atomization and, to some extent, with the fuel flow. A few enlarged frames from a close-up motion picture of the spark electrodes are presented in figure 15 to indicate the degree of electrode wetting.

Effect of fuel flow. - An increase in fuel flow (all other variables held constant) from 15 to 60 pounds per hour (fig. 11) resulted in a considerable increase in the degree of atomization from the spray nozzle because of the increase in pressure drop across the nozzle (fig. 2). At high fuel flows (above approximately 60 lb/hr), the spray formation approached that observed in still air, a result of the higher-velocity fuel droplets being less affected by air currents.

Effect of fuel temperature. - The effect of fuel temperature on spray formation at a constant fuel flow (air variables also constant) is shown in figure 12. At the conditions studied, fuel temperature had a relatively small effect on spray formation as the temperature was decreased from 74° to 9° F, where the increase in fuel viscosity was small. A noticeably poorer spray resulted when the temperature was further decreased to -30° F where the atomization is adversely affected by the greater increase in fuel viscosity. Similar results would be expected at other fuel flows in the starting range. As previously noted, the air-flow currents aided atomization, and the effect of fuel temperature on spray formation appeared to be less in the combustor than in quiescent air (reference 2).

Effect of air velocity. - The effect on spray formation of increasing combustor-inlet-air velocity from 35 to 80 feet per second at a constant

fuel flow and temperature is shown in figure 13 (air pressure and temperature also held constant). An apparent increase in the reverse air flow at the higher air velocities aided fuel atomization considerably. Liner wall and electrode wetting also increased with velocity. The fluttering of the fuel spray was more rapid at the higher velocities. An attempt to measure the frequency of the fluttering with stroboscopic light indicated a random velocity variation with time. Similar results would also be expected at other fuel flows in the starting range.

Effect of air pressure. - The effect on spray formation of a variation in combustor-inlet-air pressure (all other variables held constant) from 14 to 36 inches of mercury absolute was insignificant (fig. 14). Similarly, pressure would be expected to have little effect on spray formation at other fuel flows.

Effect of nozzle design. - Motion pictures were obtained of the spray from a variable-area fuel nozzle at the test conditions of figure 11; these motion pictures are included in the film supplement. The nearly constant high pressure drop across the variable-area nozzle (fig. 2) resulted in greatly improved fuel atomization. This effect is also indicated by a comparison of the photographs presented in figures 16 and 9(a) (nearly identical operating conditions).

Increased wall wetting was also observed with the variable-area nozzle; this may have been partly caused by the greater spray cone angle of the variable-area nozzle (100° in quiescent air) as compared with that of the fixed-area nozzle (80° when the spray was fully developed in quiescent air).

Air-Flow Patterns

As discussed previously, the effect of air-flow currents on spray formation in the J33 combustor was very pronounced. It was desirable, therefore, to determine the nature of the air-flow patterns in the combustor and to determine if combustor operating conditions affected the patterns.

Photographs of the air-flow patterns in a relatively narrow zone ($1/2$ to $3/4$ in. thick) through the center line of the combustor are shown in figure 17. The balsa-dust technique, described in the appendix, was used for tracing the air-flow patterns. The direction of the local air flow is from the large to the small end of a trace. The relative length of an individual trace is indicative of the local velocity at that point; however, the trace is located in a three-dimensional flow field and has been photographed in two dimensions only. The air-flow patterns may be more easily visualized by means of the sketches presented in figure 18. These sketches were prepared from figure 17; the arrows indicate flow direction.

The photographs in figure 17 were selected for clarity of reproduction rather than for a systematic variation in operating conditions and are representative of the flow patterns observed; however, photographs were taken over a range of combustor-inlet pressure and velocity conditions. The photographs indicate that the air-flow patterns varied more with time at a fixed combustor operating condition than with variations in combustor-inlet pressure or velocity. The local velocities varied directly with combustor-inlet velocity. The balsa-dust patterns inverted when the combustor was rotated so that the plane of light passed through a row of holes instead of between two rows of holes (fig. 4(c)).

A highly turbulent region existed about 9 inches downstream of the fuel-nozzle position in the combustor. This region is identified by the presence of balsa-dust traces which appear to indicate air flow away from a single point in all directions or by traces which cross in different directions. The latter effect is due to adjacent layers of air traveling in different directions within the zone photographed ($1/2$ to $3/4$ in. thick, along the line of sight). A reverse flow of air from the turbulent region existed in the center of the combustor in every photograph obtained. The width, shape, and length of the reverse flow varied with time. Strong local vortices existed on either side of the center in some of the patterns (fig. 17(b)). In most photographs a swirl of air existed in the vicinity of the fuel-spray and spark-plug; this swirl "bucked" the main reverse-flow air stream and formed a definite plane of turbulence (fig. 17(c)). The swirl varied in location between the two extreme positions illustrated in figure 18, and may have been responsible for the fuel-spray fluttering previously discussed.

Flame Initiation

Flame-initiation studies were undertaken to determine the effect of combustor-inlet variables (air pressure and velocity) and nozzle design on the time and manner of the flame initiation at critical ignition conditions. Because of the photographic limitations discussed in the appendix, very limited data were obtained.

Early frames of a normal-speed motion picture (24 frames/sec), taken from the side, show a small flame which failed to spread from the spark electrodes to the rest of the primary zone. This flame occurred about 1 second before the occurrence of complete flame spreading through the combustor volume. The flame spread in less than the time which elapsed between two frames of the film. High-speed motion pictures (290 frames/sec, which is approximately 12 times normal speed) obtained simultaneously showed that the flame spread through the primary zone in about 25 milliseconds, moved downstream out of the field of view of the camera, and then returned upstream. This cycling process continued for about 4 seconds (after ignition) before steady combustion was achieved.

An enlargement of a typical flame initiation sequence (filmed at 750 frames/sec, which is approximately 30 times normal speed) is presented in figure 19. The small flame (within the dotted outline in fig. 19) initiated by the spark flowed downstream from the electrodes increased in size and reversed through the center of the combustor until it spread to the complete volume of the primary zone. The air-flow patterns obtained in the cold-flow studies appeared to be present when heat was added to the fluid; however, the starting point of the reverse flow appeared to be further upstream during burning.

It was noted, in movies taken at 1500 frames per second (approximately 60 times normal speed), that a shorter flame length was associated with the variable-area nozzle than with the fixed-area nozzle. Since accurate fuel-flow measurements were not made during the starts, it is not known whether the decreased flame length was the result of finer atomization or of a possible lower fuel flow. The flame-initiation motion pictures are presented in the film supplement.

Flame Propagation in Full-Scale Engine

After flame is initiated by a spark in a single combustor, the flame must propagate to adjacent combustors in an engine. If this flame propagation fails to occur readily, over-temperature during engine starts may result from high starting fuel flows and from excessive accumulation of fuel in the combustors (reference 7).

Motion pictures of full-scale engine starts with standard fixed-area fuel nozzles (fig. 9) and with variable-area fuel nozzles (fig. 16) are presented in the film supplement. Operation of the engine with fixed-area fuel nozzles installed required considerable throttle manipulation to prevent engine over-temperature. This manipulation was required when the fuel flow for flame initiation in the two combustors equipped with spark plugs was greater than the fuel flow required for engine idle speed. A view of the turbine during one of these starts shows a slow and erratic combustor-to-combustor flame propagation around the engine. Long flames extended through the turbine during the acceleration.

The fuel flow required for flame initiation was decreased when the variable-area fuel nozzles were installed in the engine. It was found that engine idling fuel flow was sufficient for flame initiation which eliminated the throttle manipulation during the starting cycle. Rapid flame propagation around the engine was observed during these starts and acceleration occurred without excessive temperatures.

DISCUSSION

The photographic studies of turbojet-combustor fuel sprays, air-flow patterns, flame initiation, and flame propagation described herein may aid

in understanding ignition and starting results obtained in previous combustor investigations. The degree of atomization or local vaporized fuel concentration is considered an important variable in establishing the starting limits of a combustor. An accurate method of measuring the local vaporized fuel-air ratio in the combustor was unavailable for the investigation. Nevertheless, the insight gained through photographic and visual studies of fuel-spray and air-flow patterns in a combustor should aid materially in improving ignition characteristics.

Fuel volatility. - In references 1 to 4, it was found that combustor-ignition characteristics were aided considerably by an increase in fuel volatility. Thus, it was possible to decrease starting fuel flows, combustor pressure, and ignition-energy requirements with more volatile fuels. However, the ignition energies required to ignite the fuel and air mixture in a combustor (reference 3) were still many times greater than would be predicted from studies of a flowing, premixed gaseous fuel and air mixture (reference 10).

The photographs of the environment at the spark electrodes in the combustor indicate that conditions were considerably different from an ideal, homogenous fuel-air mixture. At most conditions, it appeared that ignition would not be hindered by a lack of fuel in the vicinity of the spark electrodes, rather that means of vaporizing the fuel present was required in order to form a flammable vaporized fuel and air mixture. Thus, an increase in fuel volatility and excess ignition energy would aid ignition by increasing the rate of fuel vaporization at the spark electrodes.

Fuel atomization. - In reference 7, the starting fuel flow decreased when fuel atomization was improved. From the results presented herein, this decrease may be attributed to an increase in fuel vaporization rate from finer fuel sprays. The large increases in critical starting fuel flows at low temperatures (reference 2) may be the result of decreased vaporization rate. Low temperatures decrease fuel vaporization rate and also impair fuel atomization by increasing fuel viscosity (fig. 12).

Analysis of the data of reference 2 indicated that the critical starting fuel flow approximately doubled when the combustor-inlet-air velocity was increased 25 percent by a decrease in pressure (associated decreases in air flow and temperature were small); the separate effects of pressure and velocity could not be determined from the data. As reported herein, an increase in velocity improved the fineness of the spray (fig. 13); whereas, pressure had a negligible effect (fig. 14). (However, much larger changes in pressure may be expected to have significant effects on spray formation). It appears that, at the higher velocities, the effect of improved atomization on fuel vaporization rate was offset by reduction in residence time of the liquid and vaporized fuel in the ignition environment and by the leaner over-all fuel-air ratios that exist as the velocity is increased at constant combustor-inlet pressure and fuel flow (fig. 10(b)). In addition, the decrease in pressure decreases somewhat the flammability limits of the fuel-air mixture.

Design variables. - A method for improving fuel atomization without increasing fuel flow is desired to prevent over-temperature during starting in full-scale engine operation. This goal may be achieved by fuel-nozzle design. The variable-area fuel nozzle used in this investigation operated at a nearly constant pressure drop (fig. 2), which produced fine atomization at the low fuel flows necessary for starting (fig. 16), and operated over the entire fuel-flow range of the engine (reference 6).

In references 4 and 5, it was found that moving the spark electrodes toward the center of the combustor raised the altitude starting limit. The photographs of flame spreading (fig. 19) show that the initial flame created at the spark electrodes first moved downstream and then moved upstream in the center of the combustor to fill the complete volume. Apparently, a more favorable mixture exists in the reverse-flow region (fig. 18) where the residence time for fuel vaporization is a maximum. Thus, in some combustors, flame initiation may be more easily obtained near the center of the combustor.

These results suggest that further gains in combustor starting characteristics may be obtained by controlling the fuel and air environment at the spark electrodes through spark-plug, fuel-nozzle, and combustor design. The photographic techniques described in this report are particularly suitable for assisting in the conduct of such design studies. Additional instrumentation which would permit measurement of the local velocities and the vaporized fuel and air mixtures at the ignition source is also desirable.

CONCLUDING REMARKS

The results of this photographic investigation substantiate concepts derived from results of other investigations on turbojet-engine starting and aid in understanding these results.

The study of the air-flow patterns in the transparent turbojet combustor with no combustion present substantiated the existence of reverse flow of air in the primary zone; however, the patterns fluctuated considerably. Local air turbulence in this zone improved fuel atomization at starting fuel flows, thus increasing fuel vaporization rate and aiding ignition. Air velocity had a greater effect on spray formation than did air pressure or fuel temperature; however, change in fuel-nozzle design (use of variable-area nozzle) resulted in the greatest improvement in atomization.

The combustor-liner walls and the spark electrodes were wetted by fuel in the preignition environment for all spray patterns; the amount of wetting increased with degree of atomization, fuel flow, spray cone

angle, and air velocity. The excess ignition energy required to ignite a combustor over that required to ignite a premixed gaseous fuel and air mixture may possibly be due to the energy required to vaporize the liquid fuel on the spark electrodes.

The initial flame spreading from the ignition source to the complete primary zone substantially followed the preignition air-flow patterns. Better understanding of the effect of spark electrode position and other design variables on starting performance may be obtained from this type of photographic study.

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APPENDIX - PHOTOGRAPHIC TECHNIQUES AND OPERATING METHODS

Cold-Flow Combustor Studies

Fuel-spray photographs. - The camera positions and lighting arrangements used for obtaining the reported photographic data are shown in figure 4. Motion pictures of the fuel sprays were taken from the camera position indicated in figure 4(a) at 64 frames per second (approximately 3 times normal speed) with an $f/2-7$, 15-millimeter focal length lens; 16-millimeter Eastman Kodak Super XX negative film was used. The fuel spray was illuminated by a 500-watt spot light directed into a mirror located in the duct downstream from the combustor, as shown in figure 4(a).

Still photographs of the fuel sprays were obtained with a telescoping 4 by 5-inch camera, equipped with an $f/4.5$, 190-millimeter focal length lens; Eastman Kodak Super Panchro Press Type B negative cut film was used. Illumination was provided by a stroboscopic lamp operated on single flash with a duration of about 50 microseconds. The locations of both the camera and light are illustrated in figure 4(b).

During operation of the transparent combustor the inner surface of the combustor liner was thoroughly wetted with fuel. When severe wetting occurred a small jet of high-pressure air was directed along the inner surface of the combustor dome to provide a clear area through which photographs could be obtained. This air jet was used only when it had a negligible effect on the spray pattern.

Air-flow tracers. - Air-flow patterns in the combustor were studied by obtaining photographic traces of balsa-dust particles injected into the air stream. The particles were injected at the center of, and about 1 inch upstream of the combustor dome. During these tests the fuel nozzle and holder were removed and the nozzle opening in the dome was plugged.

The method of balsa-dust preparation and injection described in reference 12 was followed with one modification: the dust was blown from a container into the air stream under pressure of oil-pumped nitrogen instead of high-pressure air because moisture in the air caused an opaque film of dust to deposit on the combustor walls.

The telescoping 4 by 5-inch camera was used to photograph the air-flow tracers. The film used to photograph the fuel sprays was also used for these photographs. The light source was a gas-filled electronic flashtube. The peak output of the tube was 93 million lumens at the rated voltage of 4000 volts; however, only 2000 volts were supplied by the power-supply circuit used in the investigation (fig. 20). The tube was mounted above the transparent combustor in a box with an adjustable ($1/8$ to $1/2$ in.) slit (fig. 4(c)). The use of a slit source of light allowed only the dust

particles in a narrow longitudinal plane to be photographed. The flash duration of the light source was variable from about 135 to 990 microseconds by combination of the parallel condensers shown in the power-supply circuit diagram (fig. 20).

After the combustor operating conditions were established, balsa dust was injected. The camera shutter was then opened in the darkened room, the flash tube fired, and the shutter closed. The pattern of the dust particles during the exposure was recorded on the film by reflected light (as contrasted with a shadow photograph). Thus, the length of the traces was a function of both particle velocity and flash duration. It was observed that the optimum length of particle trace for determining relative velocities was obtained when the flash duration was varied according to the following table:

Air velocity (ft/sec)	Flash duration (microsec)
80 - 100	135
60 - 80	270
40 - 60	360
20 - 40	495

In developing the films, the film sensitivity was effectively increased by the addition of ethanolamine (approximately 4 ml/qt of working solution) to the developer (Eastman Kodak D-76). For greater clarity of reproduction, negative prints (dark traces on a light background) were obtained by making positive films from the original negative films. Emulsion-to-emulsion contact printing was used in all steps to avoid loss of definition in balsa-dust traces.

Burning-Flow Combustor Studies

Flame-initiation motion pictures. - Flame initiations in the burning-flow combustor were photographed from the camera positions shown in figure 7. Air flow, combustor pressure, and nitrogen pressure in the fuel tank were first established, and the spark ignition circuit was closed. The quick-opening fuel valve was then opened, and ignition occurred after a few seconds delay. A time lapse was required for the high-speed camera to reach the desired constant speed. In order to synchronize the camera with the ignition, several ignition starts were made at each test condition.

The first motion pictures were obtained on 16-millimeter Eastman Kodak Kodachrome and Ektachrome color films. With the available light from the flame, satisfactory exposures could be obtained at film speeds

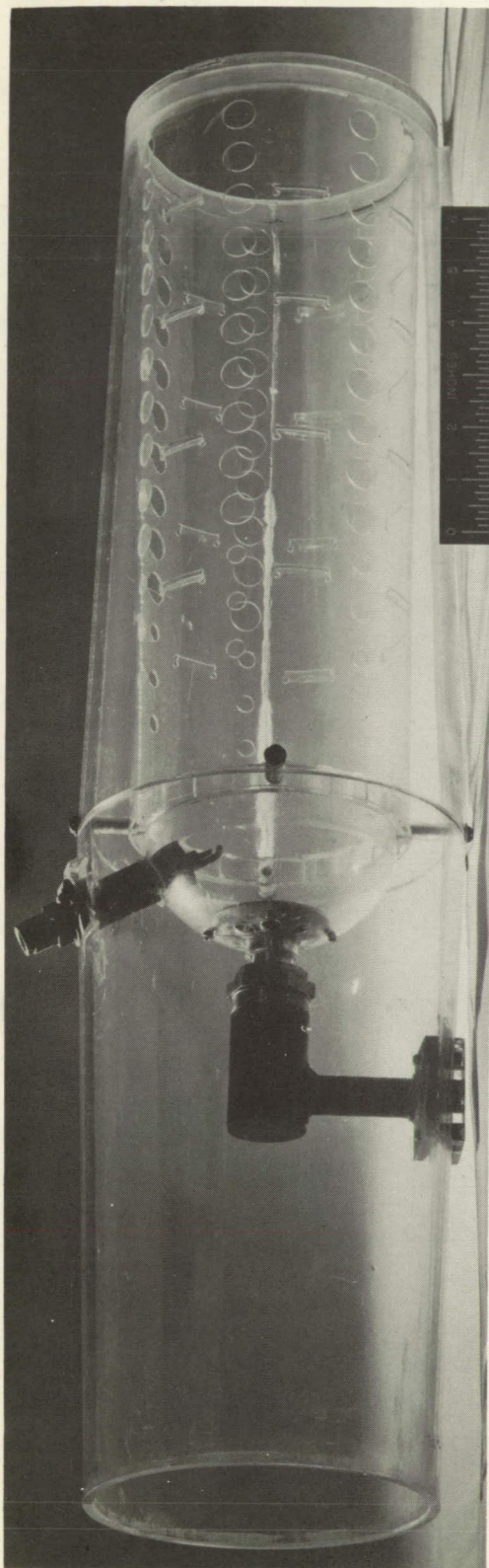
to about 300 frames per second. Since the rate of flame spreading indicated that camera speeds of 700 frames per second or higher were required, subsequent photographs were taken at 750 and 1500 frames per second on black and white film (Eastman Kodak Super XX negative film) through an f/2.0, 50-millimeter focal length lens. At low combustor-inlet pressures, equivalent to high-altitude engine starting conditions, there was insufficient light from the combustor flame for proper exposure.

Two methods were used to improve the exposure: (1) sodium chloride was added to the fuel (approximately 5 g/gal) to increase the flame luminosity, and (2) ethanolamine was used in the developer. With these additives, satisfactory results were obtained at combustor-inlet pressures as low as 18 inches of mercury absolute.

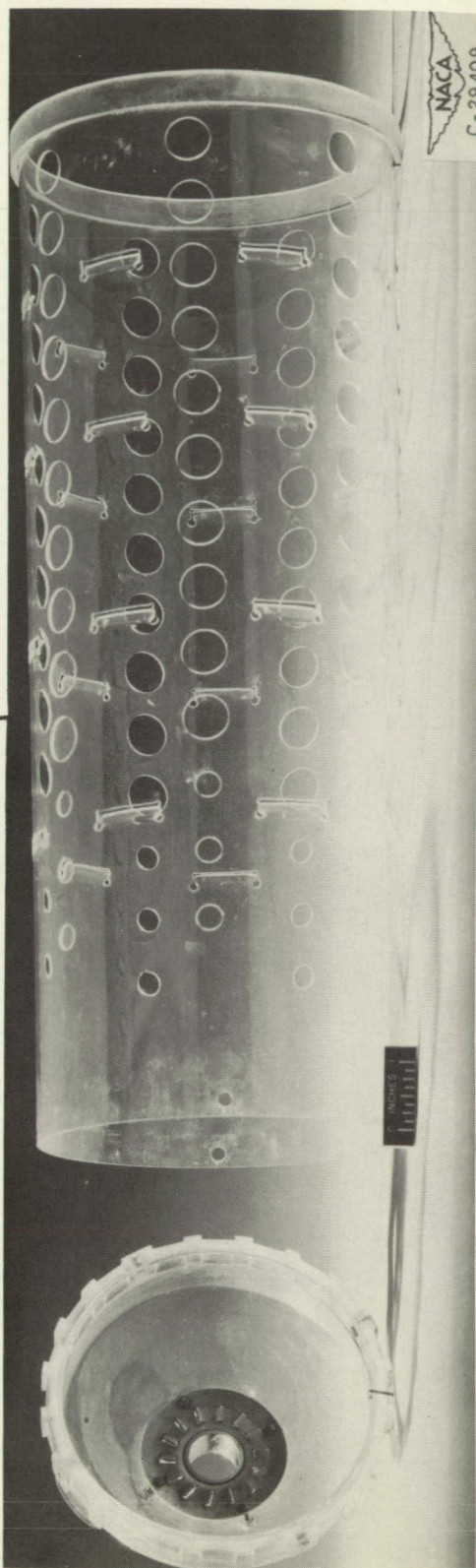
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5. Golladay, Richard L., and Bloomer, Harry E.: Investigation of Altitude Starting and Acceleration Characteristics of J47 Turbojet Engine. NACA RM E50G07, 1951.
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9. Foster, Hampton H.: Effect of Spark Repetition Rate on the Ignition Limits of a Single Tubular Combustor. NACA RM E51J18, 1951.
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11. Way, Stewart: Problems in the Development of Turbo-Jet Combustion Chambers. Scientific Paper No. 1421, Westinghouse Res. Labs., March 8, 1949.
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(a) Assembly.



(b) Liner and dome.

Figure 1. - Transparent plastic combustor.

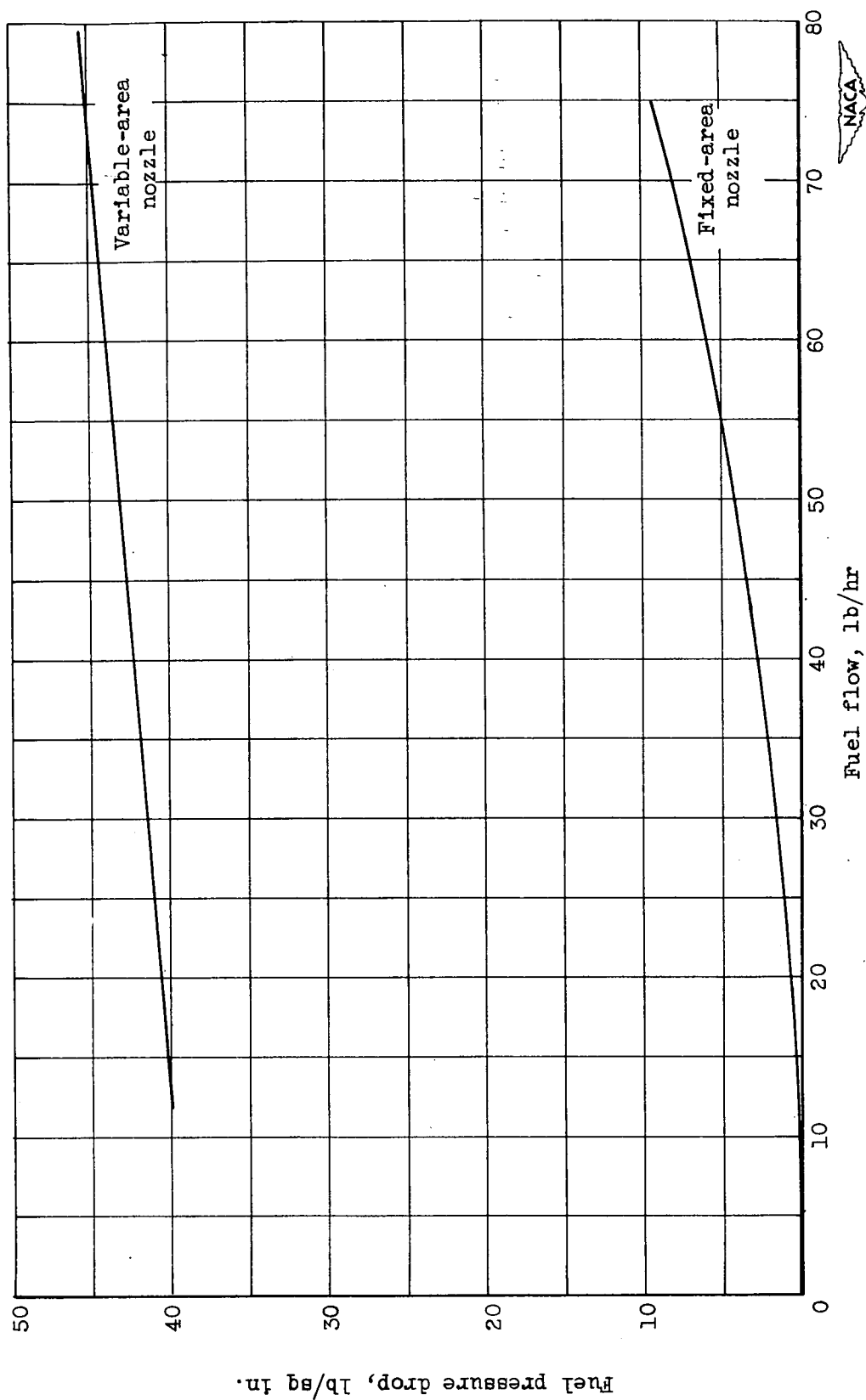


Figure 2. - Variation of fuel pressure drop with fuel flow for fixed- and variable-area nozzles.

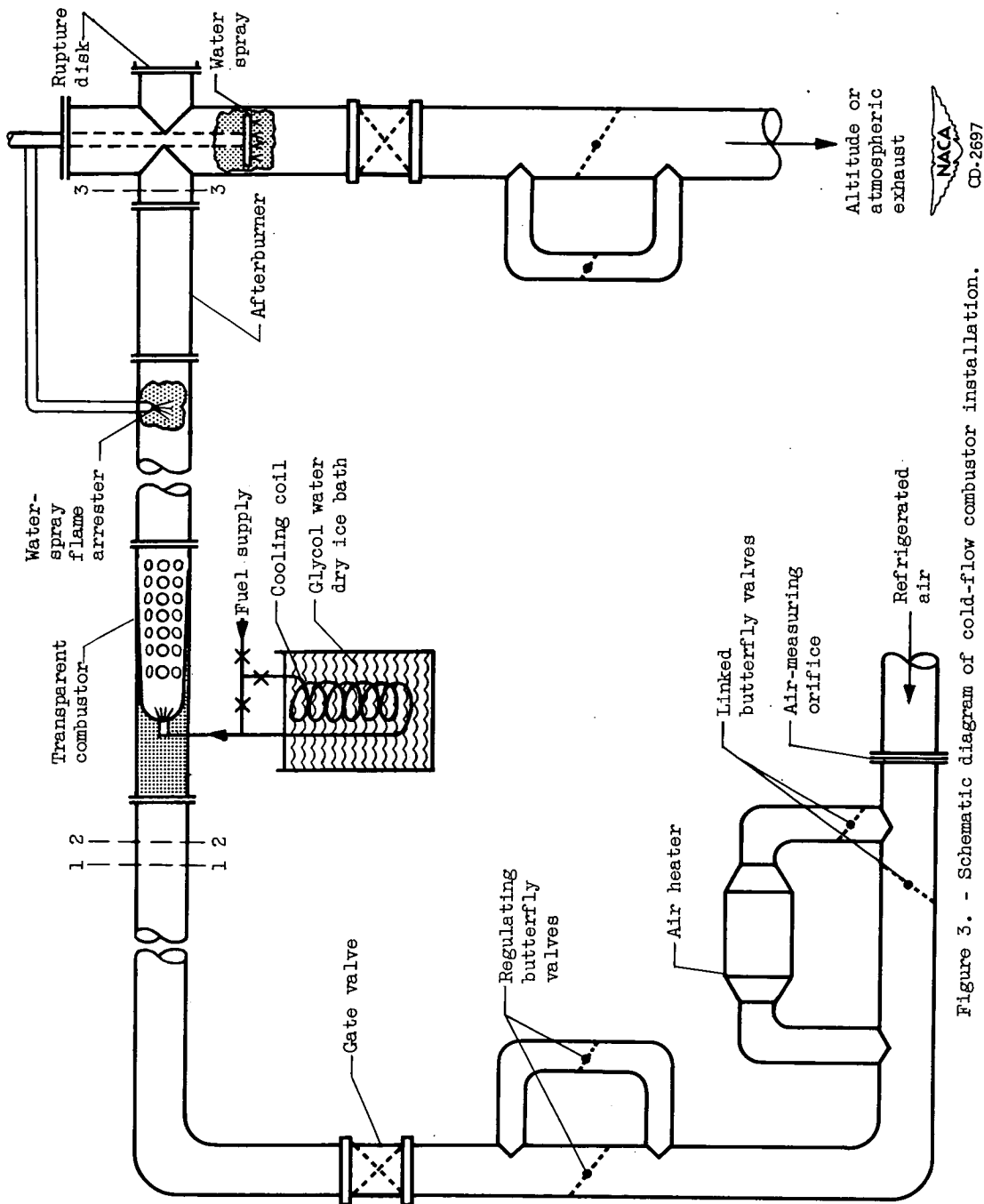
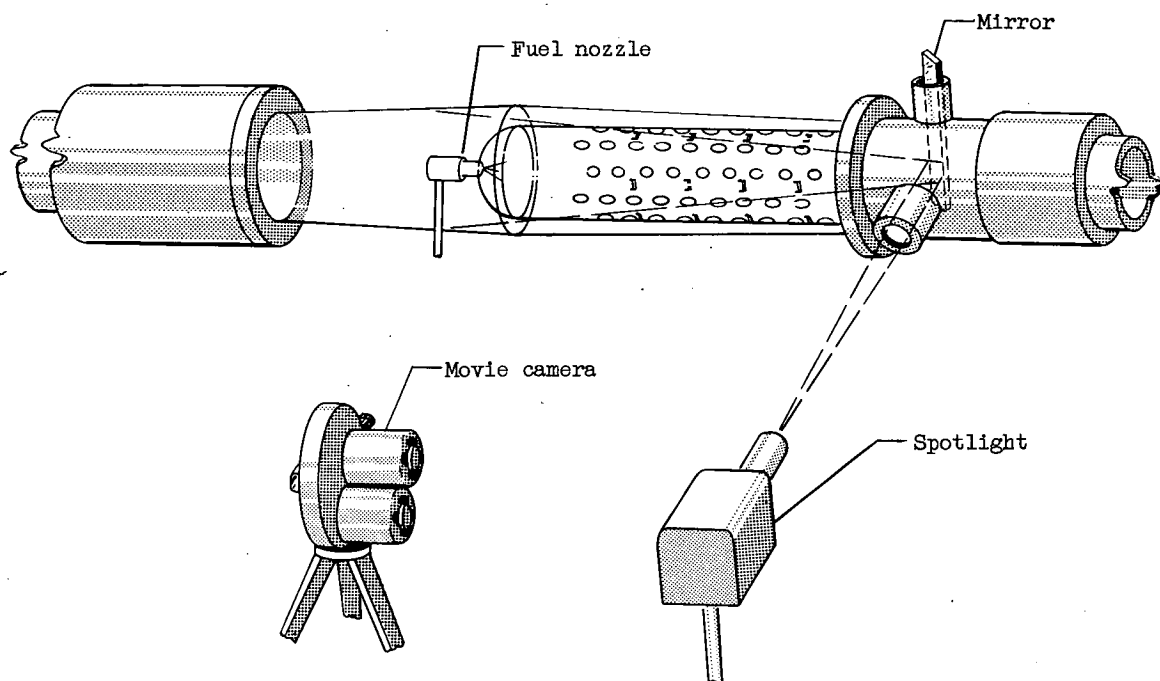
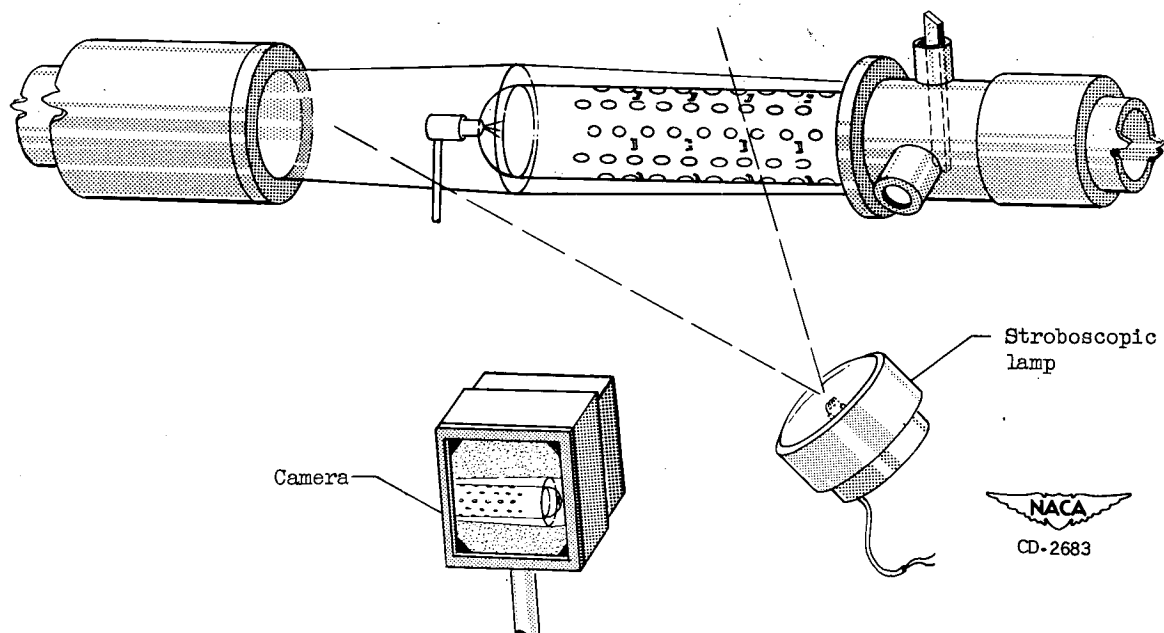


Figure 3. - Schematic diagram of cold-flow combustor installation.

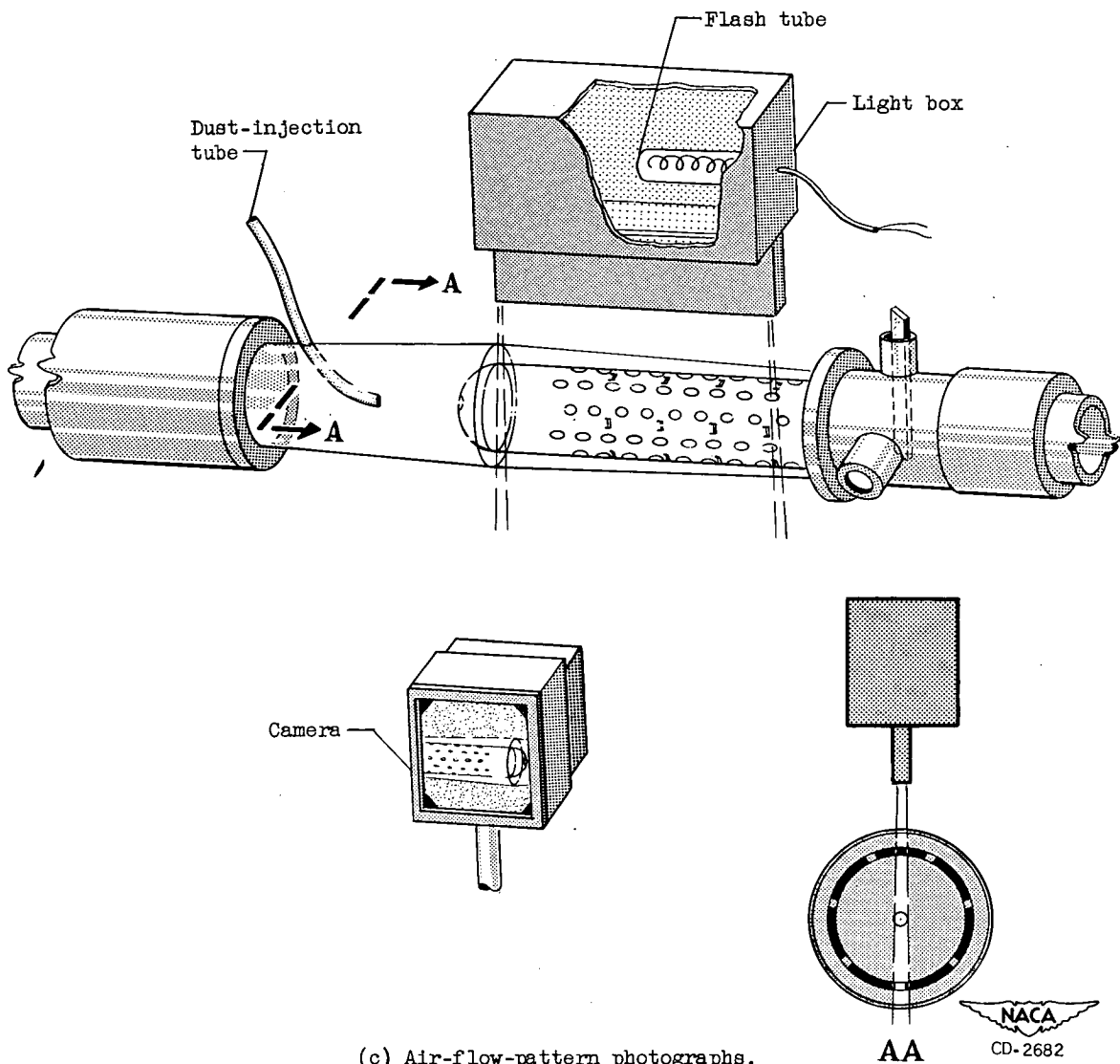


(a) Fuel-spray motion pictures.



(b) Fuel-spray still photographs.

Figure 4. - Camera positions and lighting arrangements used in cold-flow combustor photographic studies.



(c) Air-flow-pattern photographs.

Figure 4. - Concluded. Camera positions and lighting arrangements used in cold-flow combustor photographic studies.

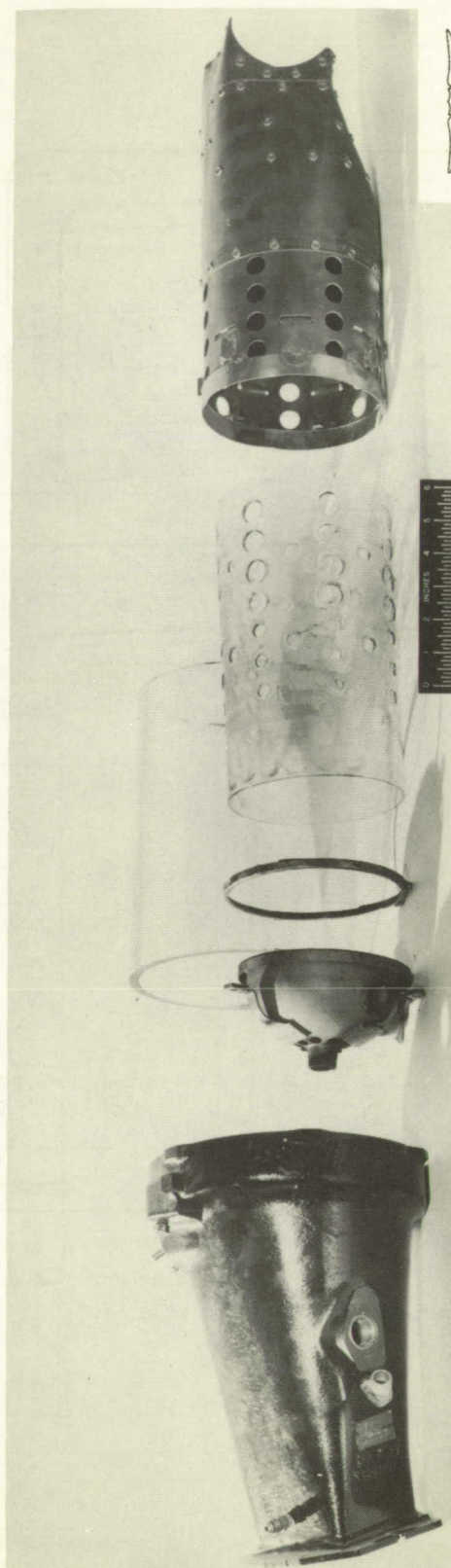


Figure 5. - Exploded view of burning-flow combustor.

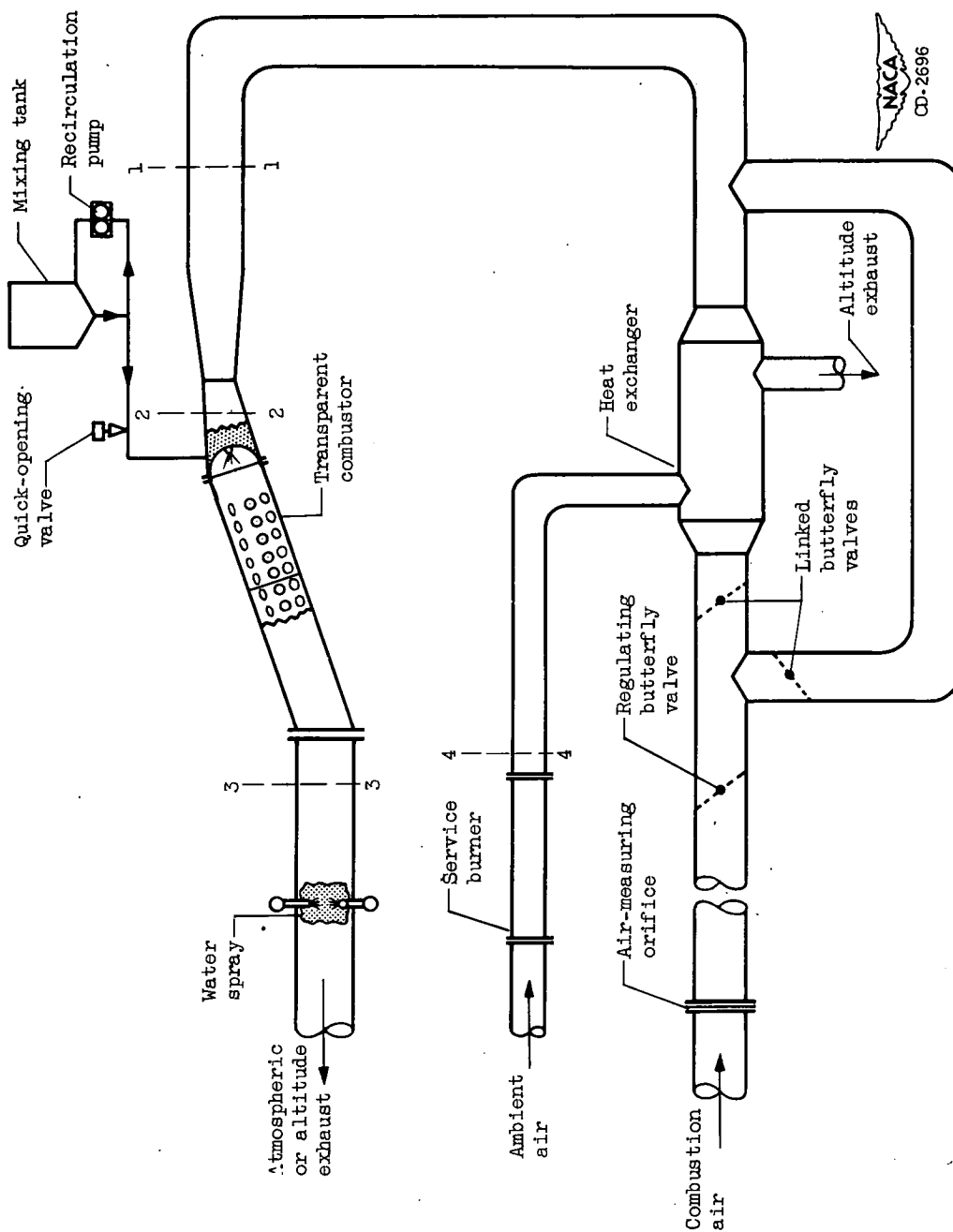


Figure 6. - Schematic diagram of burning-flow combustor installation.

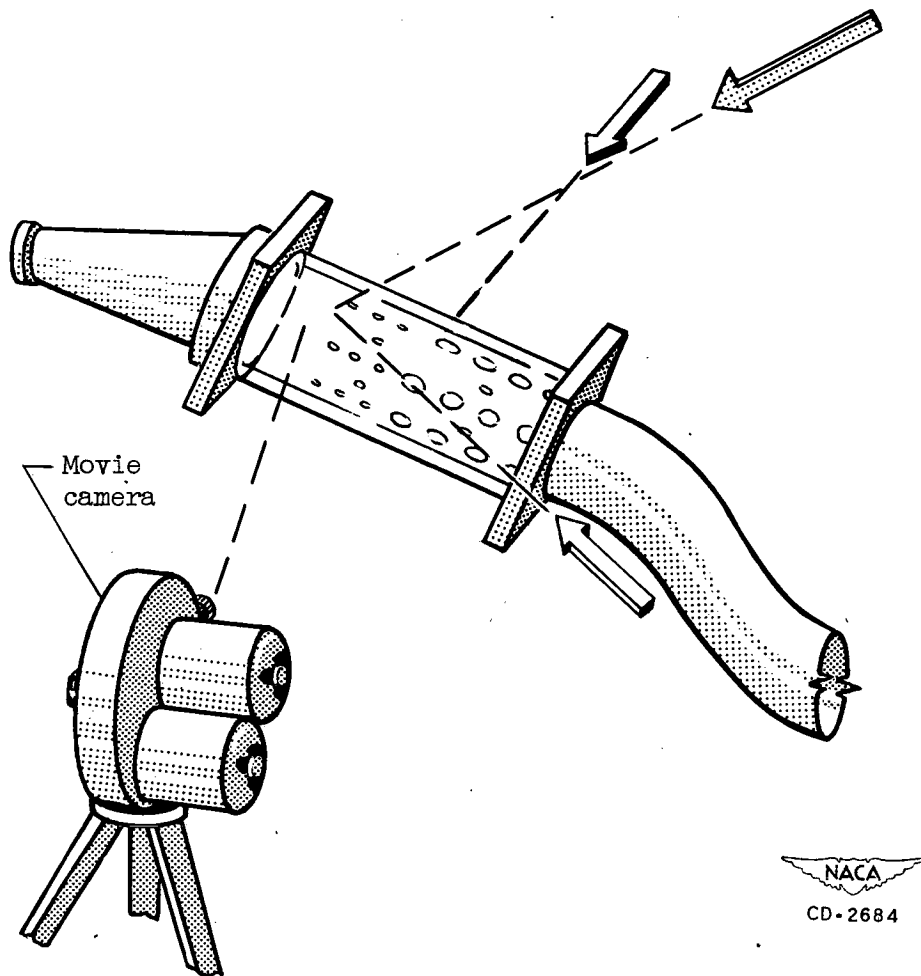
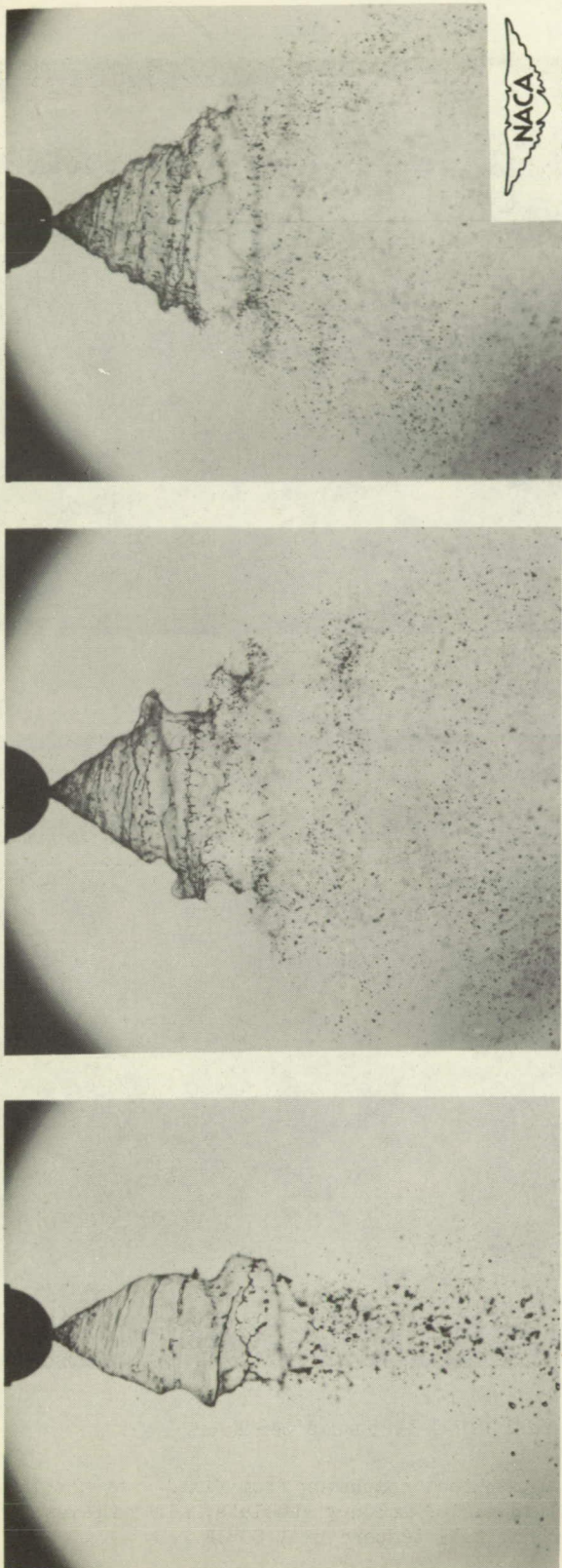


Figure 7. - Camera positions used in burning-flow combustor photographic studies.

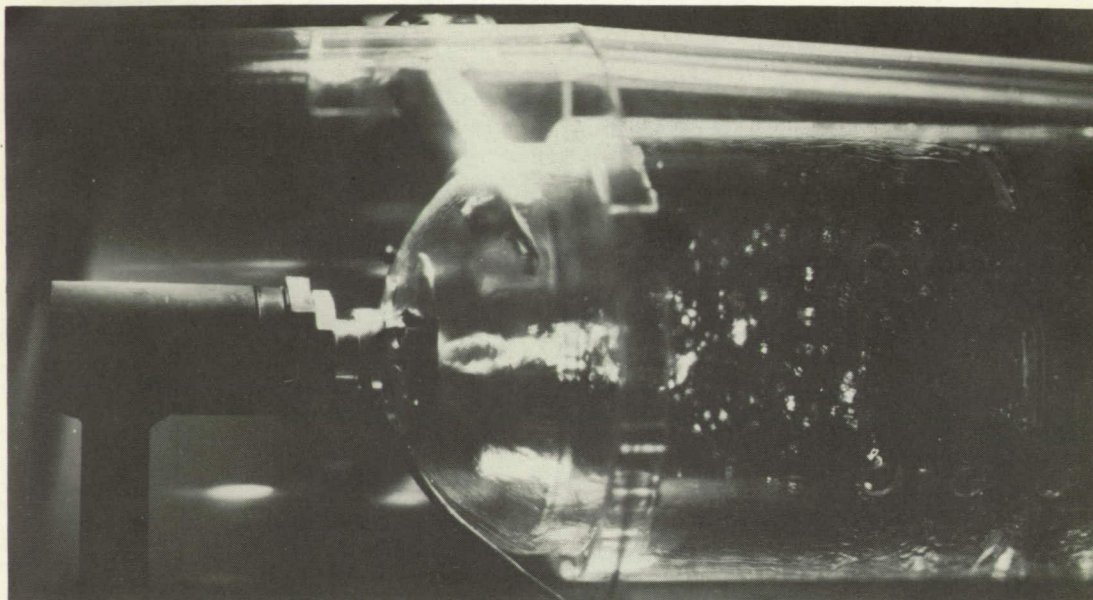


(a) Fuel flow, 40 pounds per hour.

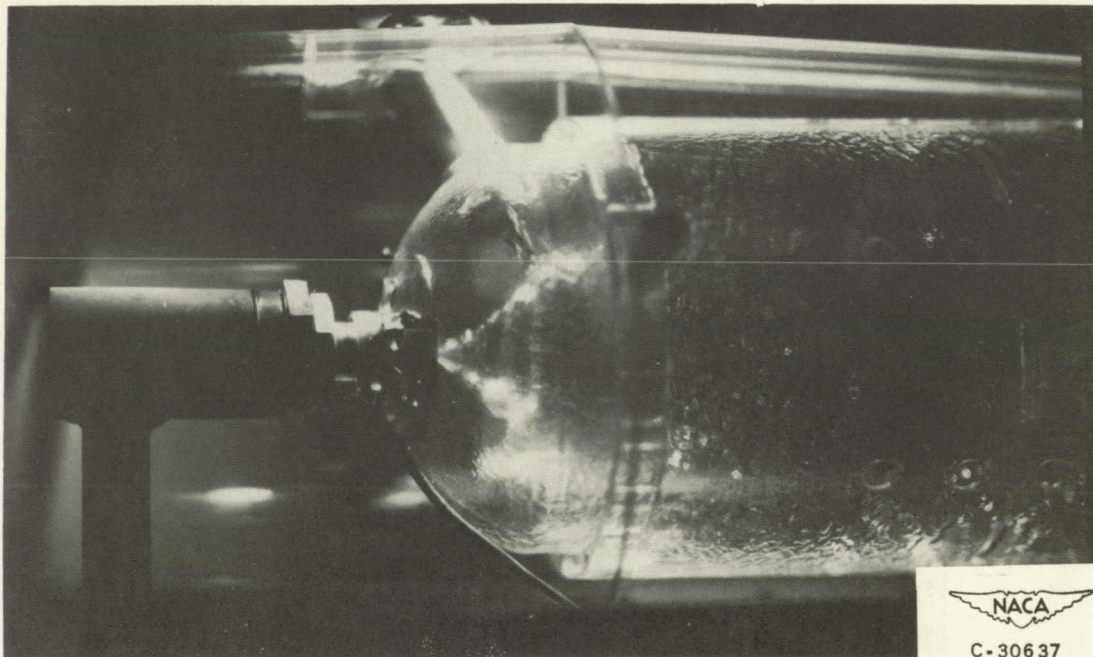
(b) Fuel flow, 65 pounds per hour.

(c) Fuel flow, 80 pounds per hour.

Figure 8. - Fixed-area fuel nozzle spraying into quiescent air.

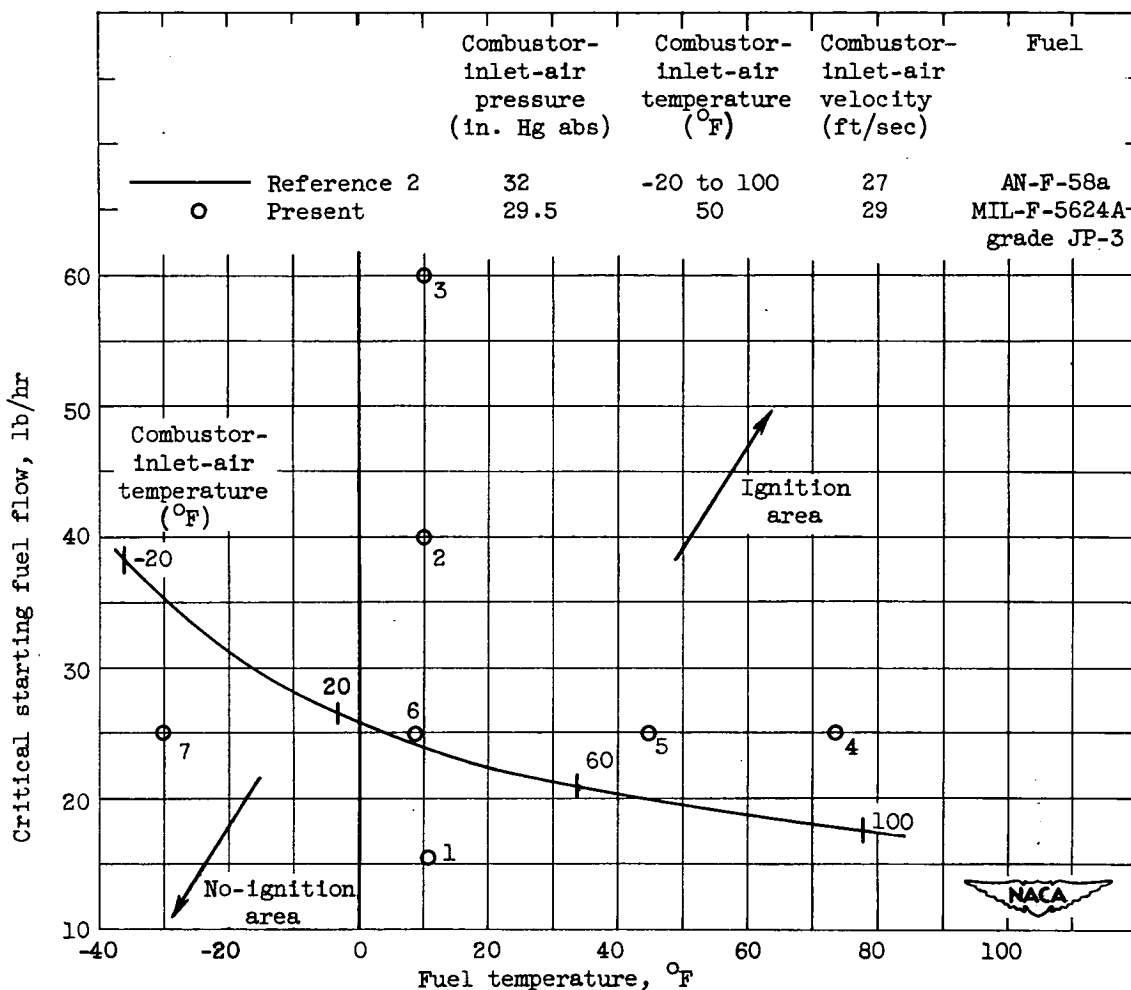


(a) Fuel flow, 29 pounds per hour.



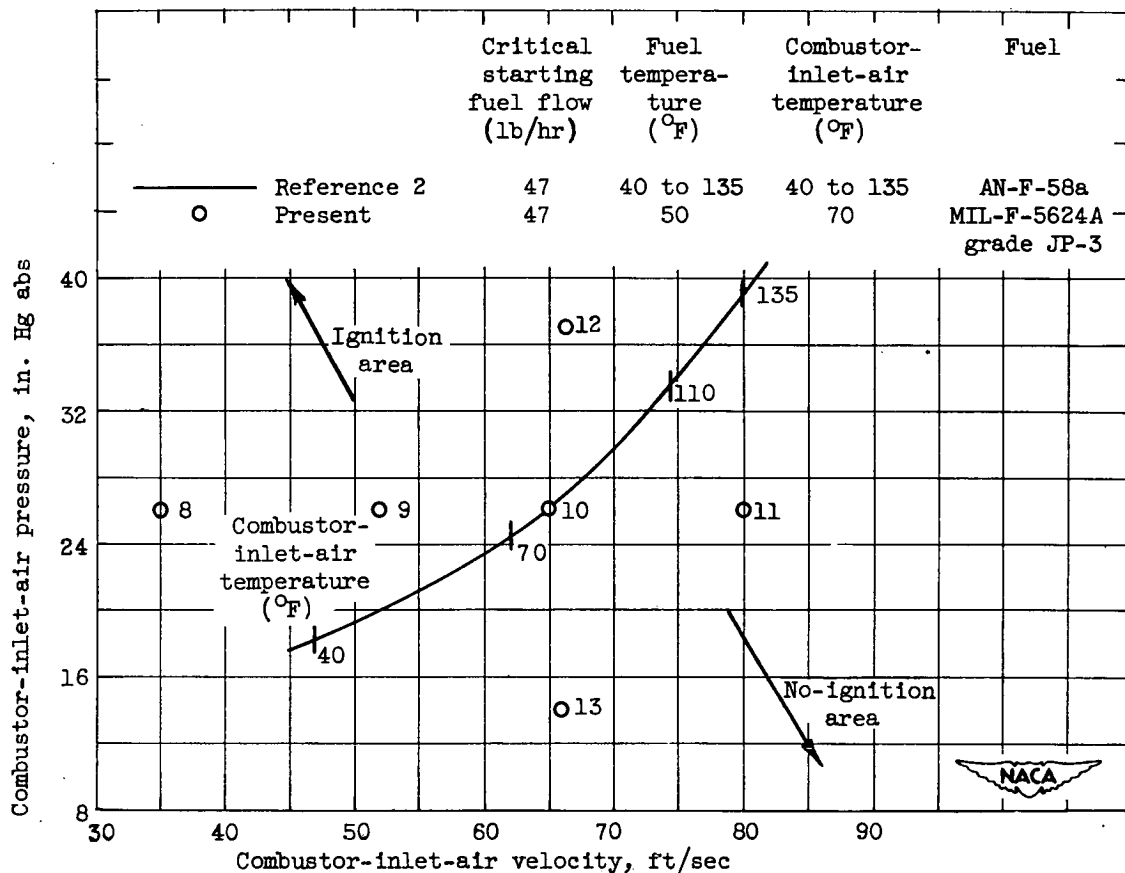
(b) Fuel flow, 44 pounds per hour.

Figure 9. - Fuel spray in transparent combustor from fixed-area nozzle. Combustor conditions: pressure, 27 inches of mercury absolute; air temperature, 62° F; air velocity, 26 feet per second; fuel temperature, 80° F.



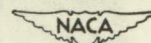
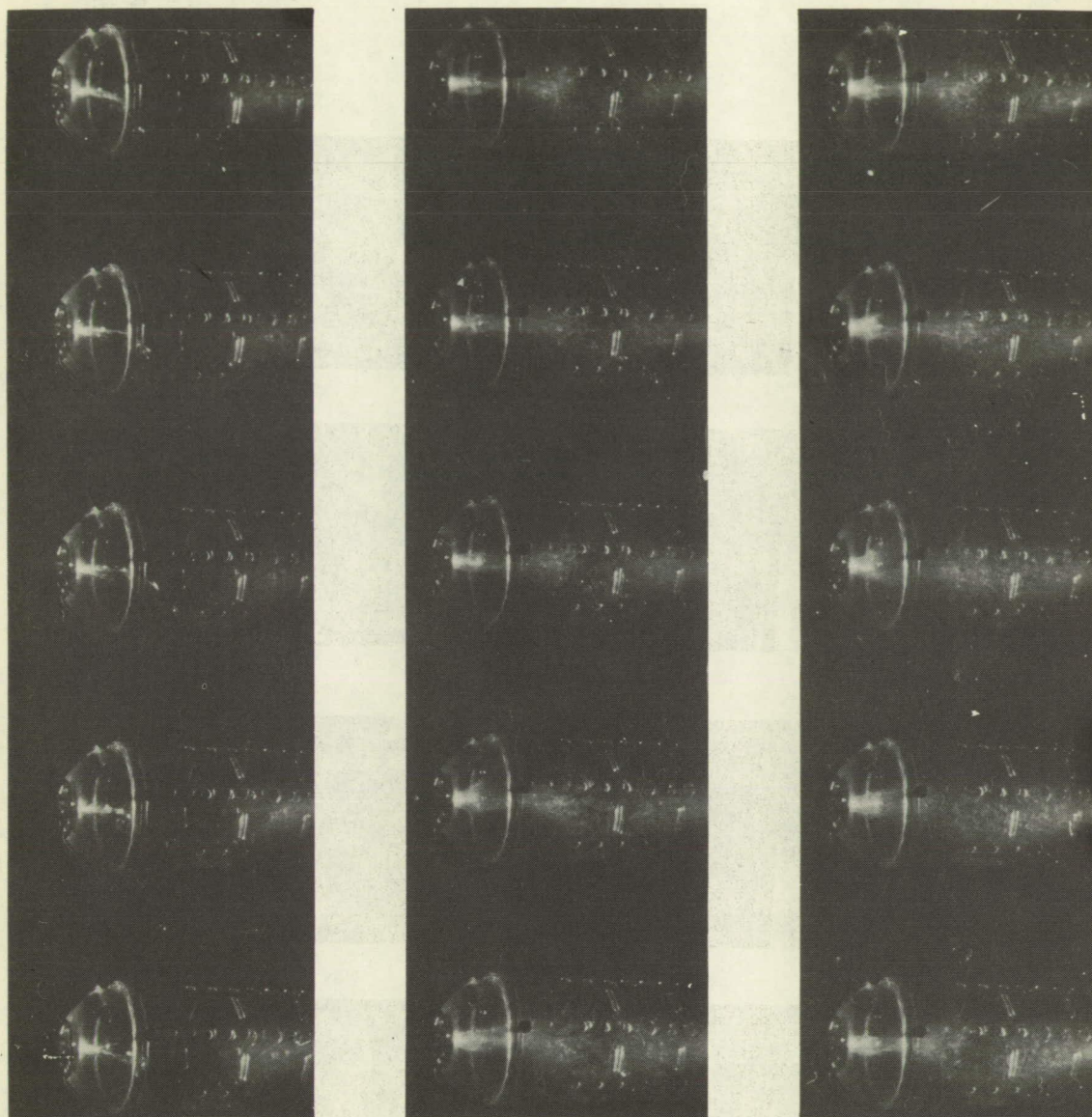
(a) Fuel flow as function of fuel temperature.

Figure 10. - Ignition-limit curves from reference 2 and test conditions of present investigation.



(b) Combustor-inlet-air pressure as function of combustor-inlet-air velocity.

Figure 10. - Concluded. Ignition-limit curves from reference 2 and test conditions of present investigation.



C-30638

(a) Point 1 (fig. 10(a));
fuel flow, 15.5 pounds
per hour.

(b) Point 2 (fig. 10(a));
fuel flow, 40 pounds per
hour.

(c) Point 3 (fig. 10(a));
fuel flow, 60 pounds per
hour.

Figure 11. - Effect of fuel flow on appearance of fuel spray from fixed-area nozzle.
Combustor-inlet conditions: pressure, 29.5 inches of mercury absolute; air temperature, 50° F; air velocity, 29 feet per second; fuel temperature, 10° F.



(a) Point 4
(fig. 10(a));
fuel temperature,
740 F.

(b) Point 5
(fig. 10(a));
fuel temperature,
450 F.

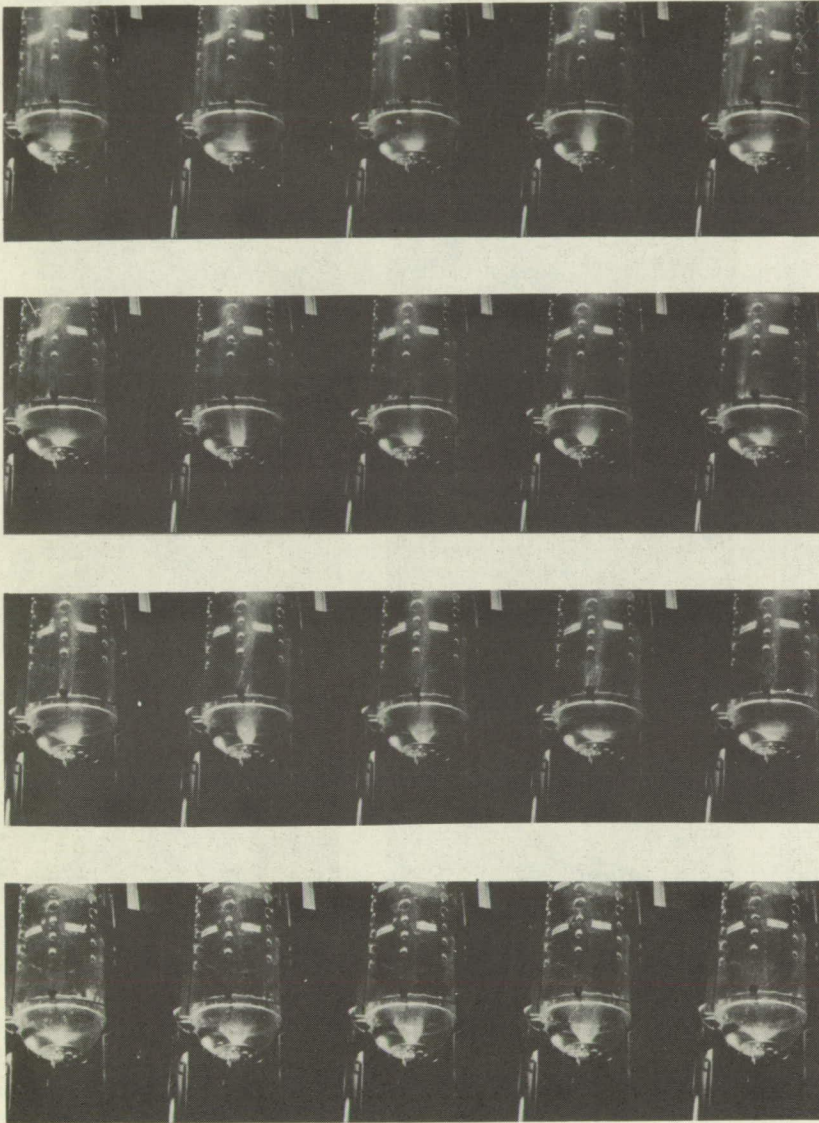
(c) Point 6
(fig. 10(a));
fuel temperature,
90 F.

(d) Point 7
(fig. 10(a));
fuel temperature,
-300 F.



C-30639

Figure 12. - Effect of fuel temperature on appearance of fuel spray from fixed-area nozzle. Combustor-inlet conditions: pressure, 29.5 inches of mercury absolute; air temperature, 50° F; air velocity, 29 feet per second; fuel flow, 25 pounds per hour.



(a) Point 8
(fig. 10(b));
air velocity,
35 feet per
second.

(b) Point 9
(fig. 10(b));
air velocity,
52 feet per
second.

(c) Point 10
(fig. 10(b));
air velocity,
65 feet per
second.

(d) Point 11
(fig. 10(b));
air velocity,
80 feet per
second.

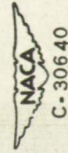
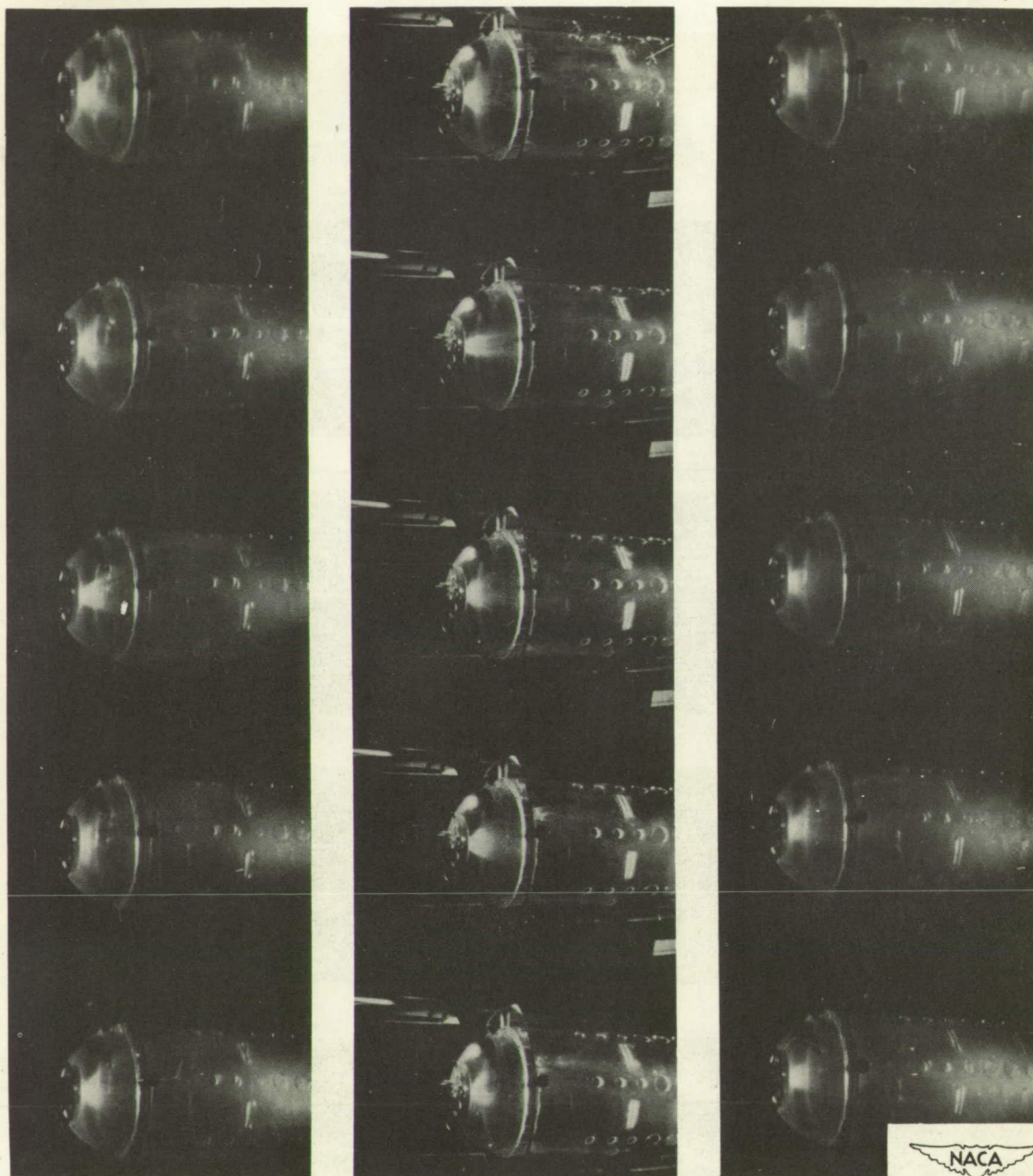


Figure 13. - Effect of combustor-inlet air velocity on appearance of fuel spray from fixed-area nozzle. Combustor-inlet conditions: pressure, 26 inches of mercury absolute; air temperature, 50° F; fuel flow, 47 pounds per hour; fuel temperature, 70° F.

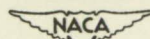


(a) Point 13 (fig. 10(b));
inlet air pressure,
14 inches of mercury
absolute.

(b) Point 10 (fig. 10(b));
inlet-air pressure,
26 inches of mercury
absolute.

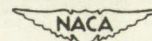
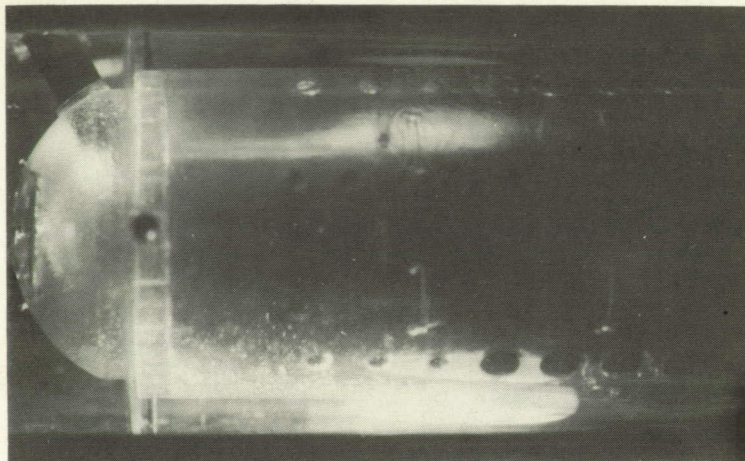
(c) Point 12 (fig. 10(b));
inlet-air pressure,
37 inches of mercury
absolute.

Figure 14. - Effect of combustor-inlet-air pressure on appearance of fuel spray from fixed-area nozzle. Combustor-inlet conditions: air temperature, 50° F; air velocity, 66 feet per second; fuel flow, 47 pounds per hour; fuel temperature, 70° F.



C-30642

Figure 15. - Fuel on spark electrodes in transparent combustor prior to ignition.
Combustor-inlet conditions: pressure, 32.6 inches of mercury absolute; air velocity, 28 feet per second; air temperature, 87° F; fuel flow, 30 pounds per hour.



C-30643

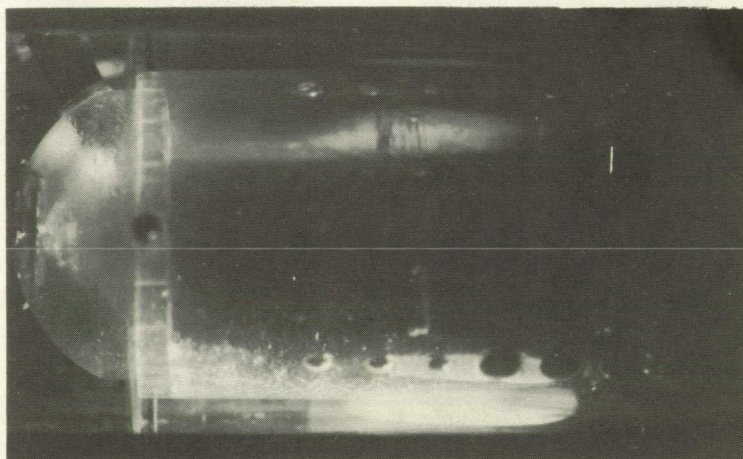
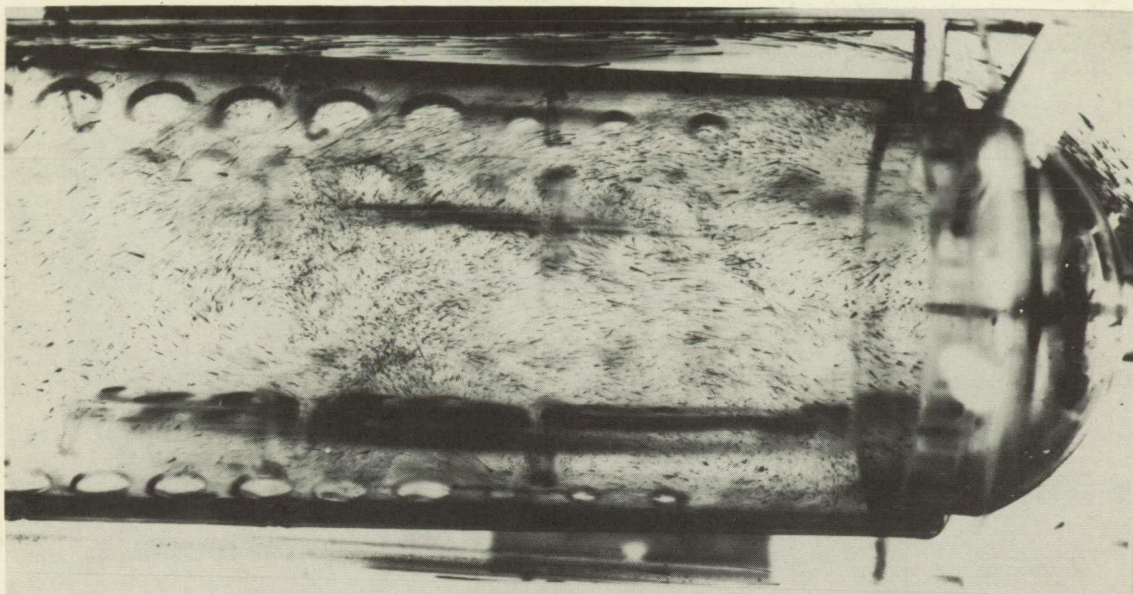
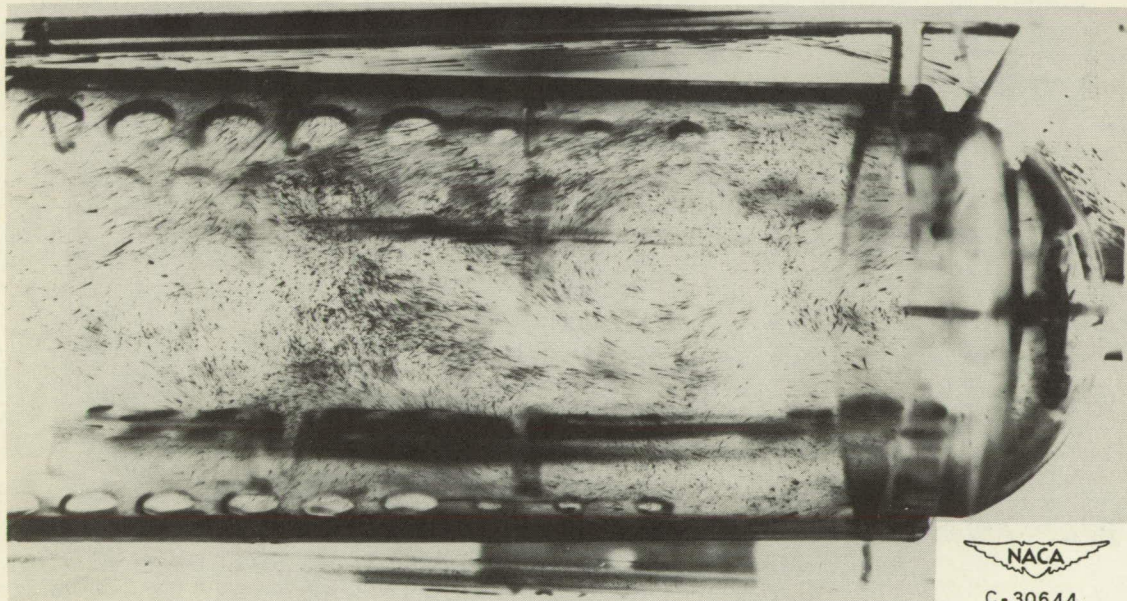


Figure 16. - Typical photographs of spray from variable-area nozzle. Combustor conditions: pressure, 29.3 inches of mercury absolute; air velocity, 25 feet per second; air temperature, 62° F; fuel flow, 28.5 pounds per hour; fuel temperature, 80° F.

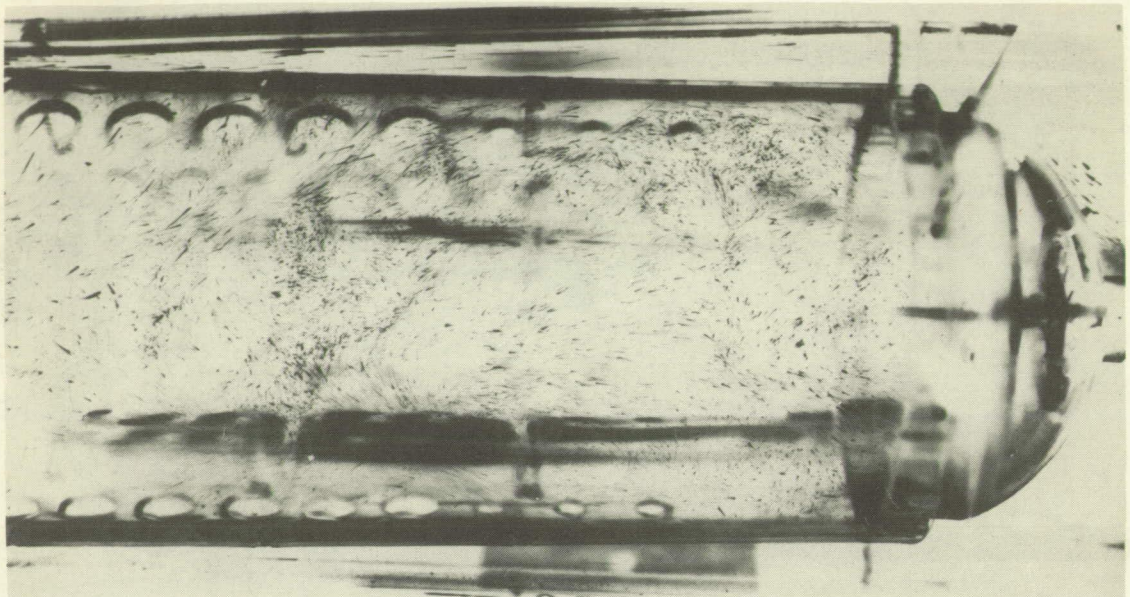


(a) Combustor-inlet conditions: pressure, 28.6 inches of mercury absolute; air temperature, 60° F; air velocity, 21.1 feet per second; flash duration, 495 microseconds.



(b) Combustor-inlet conditions: pressure, 28.6 inches of mercury absolute; air temperature, 60° F; air velocity, 21.1 feet per second; flash duration, 495 microseconds.

Figure 17. - Photographs of air-flow patterns in transparent combustor. Patterns shown by balsa-dust tracers.



(c) Combustor-inlet conditions: pressure, 28.6 inches of mercury absolute; air temperature, 60° F; air velocity, 21.1 feet per second; flash duration, 495 microseconds.

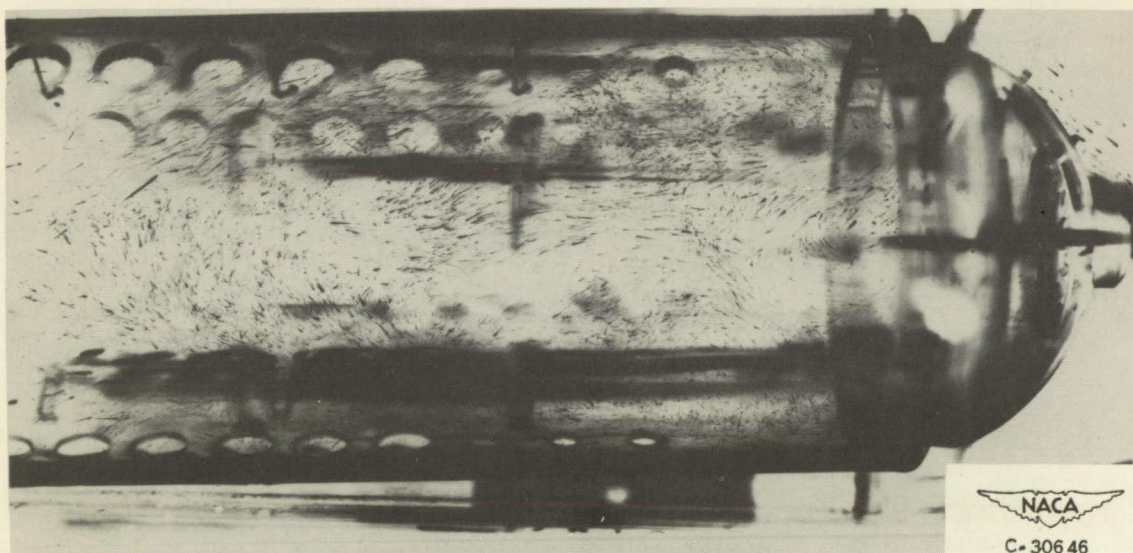


(d) Combustor-inlet conditions: pressure, 28.6 inches of mercury absolute; air temperature, 60° F; air velocity, 36.1 feet per second; flash duration, 495 microseconds.

Figure 17. - Continued. Photographs of air-flow patterns in transparent combustor. Patterns shown by balsa-dust tracers.



(e) Combustor-inlet conditions: pressure, 28.6 inches of mercury absolute; air temperature, 60° F; air velocity, 36.1 feet per second; flash duration, 495 micro-seconds.



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C-30646

(f) Combustor-inlet conditions: pressure, 28.6 inches of mercury absolute; air temperature, 60° F; air velocity, 36.1 feet per second; flash duration, 360 micro-seconds.

Figure 17. - Concluded. Photographs of air-flow patterns in transparent combustor. Patterns shown by balsa-dust tracers.

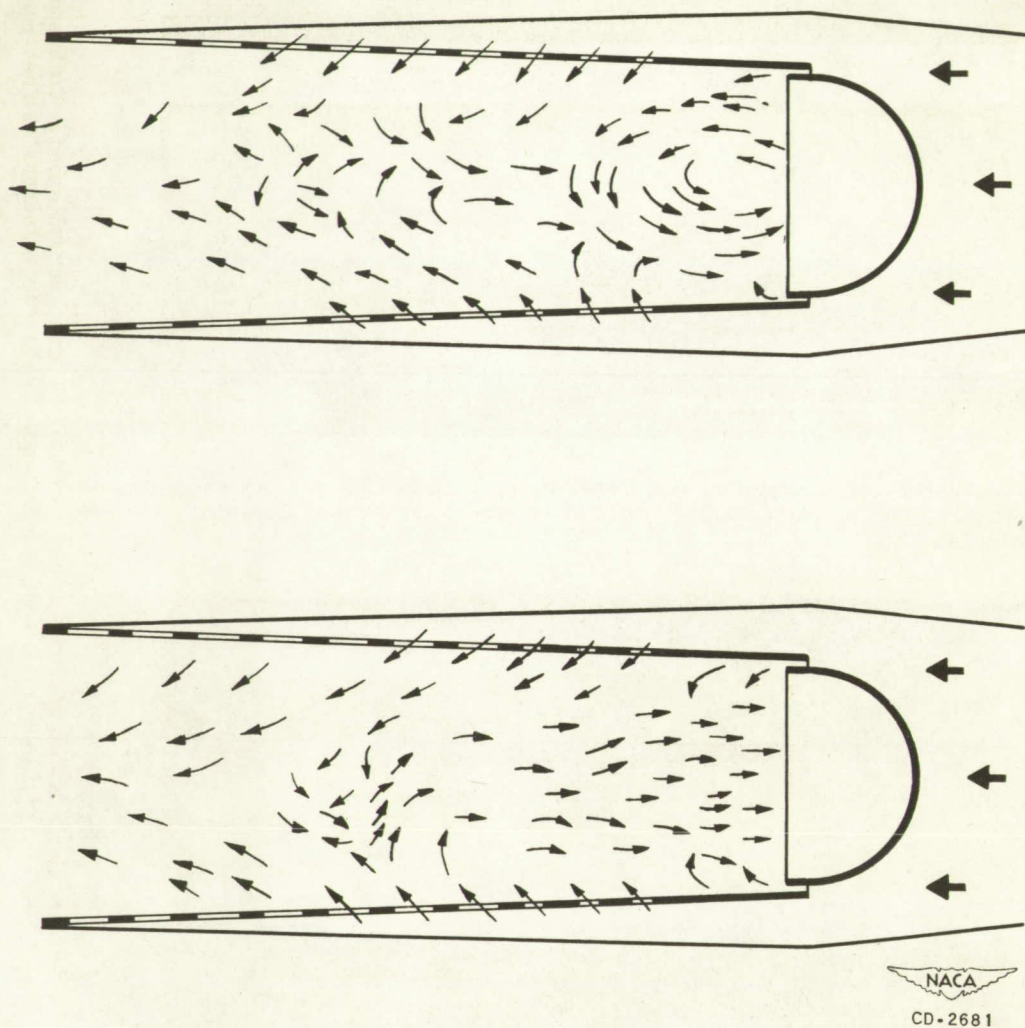
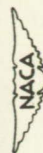
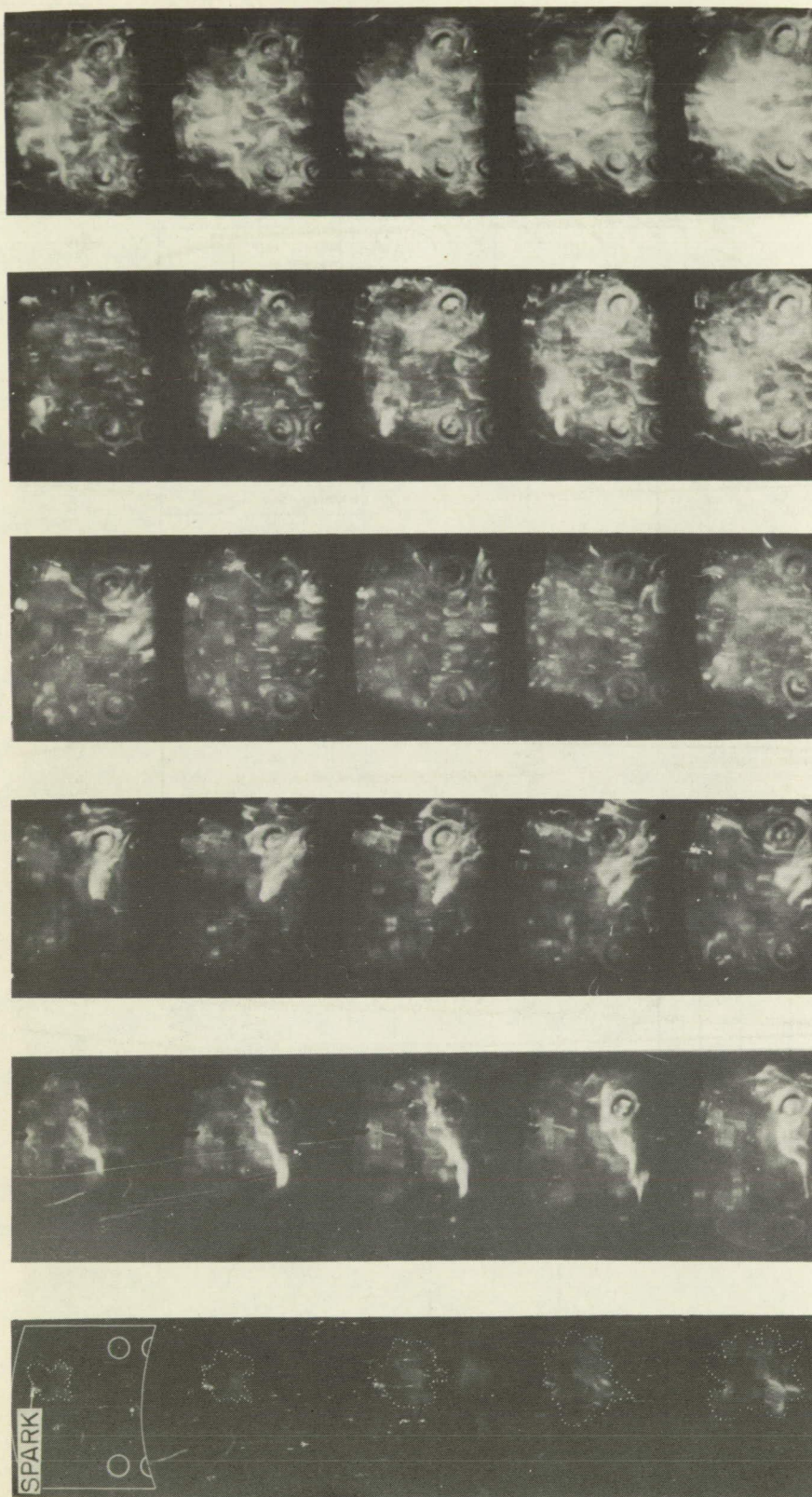


Figure 18. - Typical air-flow patterns shown by balsa-dust flow tracers.



C-30710

Figure 19. - Enlargement from a flame-initiation motion picture taken at 30 times normal speed. Combustor inlet conditions: pressure, 18 inches of mercury absolute; air temperature, 40° F; air velocity, 39 feet per second.

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